

A THREE DIMENSIONAL NUMERICAL INTERACTION MODEL FOR THE FIXATION OF MANDIBULAR FRACTURES

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Abstract- Two and three dimensional finite element models (FEM) were developed to simulate the behavior of a fractured jaw bone and the fixation materials. Mini-plates with various geometric and material properties and screw combinations were considered. Their effects on the variation of maximum stress contours were investigated.

The geometric and material properties of the plate, screw and bone were seen to play important roles in effecting the relative displacement at the fractured surface and the spatial variation of the maximum stress across the jaw bone. Softer materials yielded less stress concentrations around the screws while increasing the relative deformation at the fractured surface and stiffer ones caused higher stress concentrations while decreasing the displacements. Results were also seen to be dependent on the loading and the need for the use of patient specific 3D solutions was emphasized.

Keywords—Mandible,fracture,miniplate, FE modeling

I. INTRODUCTION

In oral and maxillofacial surgery different techniques have been used for the fixation of mandibular fractures, one of which is the, miniplate osteosynthesis. Even though several mini-plates and screws with different geometric designs and material characteristics are available, the geometric and elastic properties of these materials, number and locations of the screws have not been yet definitely demonstrated.

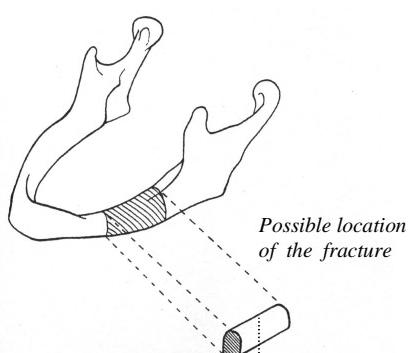


Fig.1 A slice taken from the mandible

In early bio-mechanical studies [1] numerical analyses were based on the assumption that the horizontal part of the mandible (Fig.1) behaved as a cantilever producing tensile and compressive stresses, above and below the neutral axis, respectively . The aim of this study is to determine the most suitable material, shape and fixation technique for a certain type of jaw fracture at corpus.

(Fig.1). The stress contours derived from the internal moments which were caused by a load at the tip of the cantilever of a simple 2D cantilever model, is shown in the Fig.2 , [2]. The case essentially describes a moment dominant problem when the load is sufficiently far from the fracture.

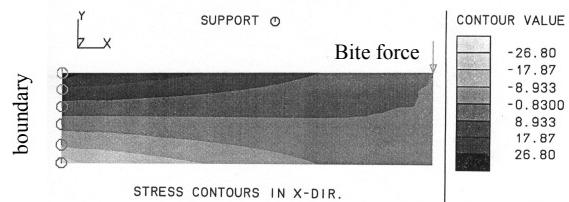


Fig. 2. Stress distribution within the 2D uncracked mandible

Since the maximum tensile and compressive stresses occur at the upper most fibers of the bone, miniplates are intended to be located at the upper most fibers.

II. METHODOLOGY

1) *The 2D mathematical model:* The 2D coupled bone-plate interaction model [3,4] which is composed of 2D thick shell elements is shown, in Fig.3. The fracture was assumed to occur at a vertical plane and the boundary nodes were assumed to be fixed. Loading was represented by a vertical incisor bite force of 200 N at the tip of the cantilever.

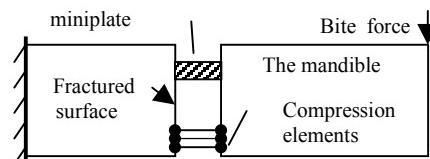


Fig.3 The 2D cracked-Fixed cantilever model

Two main criteria were considered for a proper healing process. These were the tolerable relative displacement at the fractured surface (Fig.4) and target stress distribution across the fractured bone.

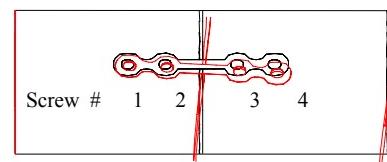


Fig.4 The deformation at the fractured surface

The ratio of elastic modulus of the mini-plate to that of the bone was assumed to vary from 0.1,1 and 10, and the target stress distribution of the cracked model

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was assumed to resemble to that of the un-cracked one, as shown in the Fig.2.

Result indicated that when the plate was assumed to be welded to the bone, ie: the effects of screws were ignored, a stiffness ratio of 10 yields the best stress distribution among the other two. However this was not a general conclusion, since the effective length of the plate, loading and the material properties of the screws were assumed be constant. Thus the model was extended into 3D. Within the scope of this only the results related to the 3D study was presented.

2) The material properties :

The bone was assumed to be composed of the cortical and cancellous parts and various material properties were assigned to all contributing elements.

2.1 The bone:

In order to take into account the age of the patient, three different material properties, were assumed. Table.1, summarizes the values for the elastic modulie, decribing the cortical bone of a child, a normal person and an old person.

Cortical bone	Elastic Modulus (N/mm ²)	Poisson's Ratio
Soft	7500	0.33
Normal	15000	0.33
Hard	22500	0.33

Table.1 Different material properties for the cortical bone

2.2 The fractured surface:

To represent the different healing phases of a patient, material properties of the fracture was assumed to vary from 0 to 15000, as given in Table.1.

Healing phase	Elastic modulus (N/mm ²)
No bond	0
Very low	250
Medium	500
Hardening	750
Recovered	15000

Table.2 Material properties of the fracture zone

The lowest value indicates the value at a time immediately after the surgical operation and the highest value occurs at a time when 100% healing occurs. The thickness of the fictitious contact element was assumed to be 2 mm.

2.3 The fixation materials: Table.3 summarizes the variation of the materials , ranging from gold, the softest, to aluminum ceramic,,the hardest.

Fixation materials	Elastic modulus (N/mm ²)
Gold (Au)	71.000
Titanium (Ti)	110.000
Platinum (Pt)	150.000
Stainless steel (Fe)	210.000
Aluminum Ceramic	345.000

Table.3 The material properties of the fixation materials

The length and the diameter of the screws were assumed to be 7 and 2 mm, respectively.

3) The 3D FEM : The professional FE code LUSAS Ver.13 [3] was used to generate and run the 3D screw-bone-plate interaction model. The cancellous and hollow character of the bone was modeled by using a total of 1972 solid elements and 2795 nodes, as shown in Fig.5.

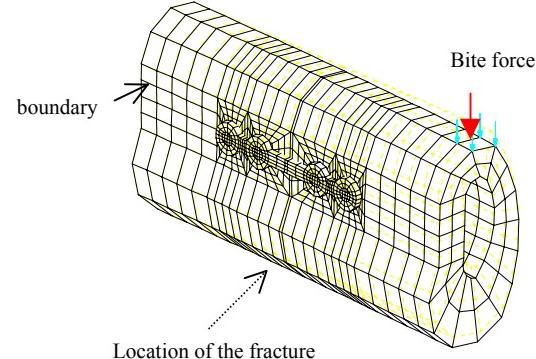


Fig.5 The 3D bone-plate-screw-fracture FE model

A vertical fracture was assumed to occur at a mid distance from the tip and four holes were used to represent the application points of the screws. Effects of the screw combinations and miniplate geometry were considered.

III. RESULTS OF THE 3D STRESS ANALYSES

Typical stress contours at a titanium plate attached to a normal aged bon are shown, in the Fig.6.

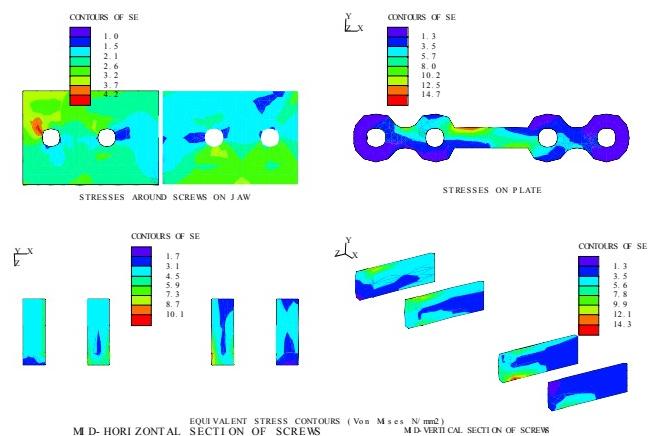


Fig.6 Stresses developed at the bone and fixation materials

The stresses at mid horizontal and vertical sections of the screws and for the plate and the stress distribution across the mini-plate are shown. It is seen that the maximum metallic stresses (Von-Mises) occur at the 3rd screw causing stress concentrations at the bone around the 1st screw.

The shear and principal stresses developed at the cortical bone and the von-Mises stresses developed at the metallic components are plotted across the vertical and horizontal planes as shown in the, Fig's.7 and 8, respectively.

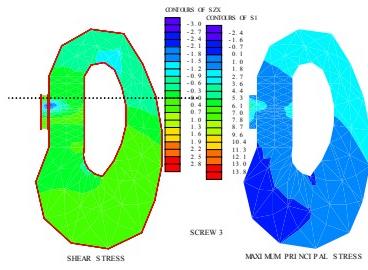


Fig.7 Stress contours at a vertical slice passing through the screw #3.

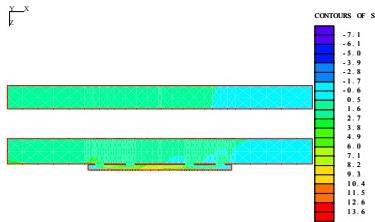


Fig.8 The stress contours across the horizontal slice of Fig.7.

The stress concentrations in the vicinity of the screws and plate are noticeable. It is worth noting that usually Von-Mises stresses are preferred to define the stresses developed in metals. Similarly, maximum principal stress components are generally used for the bone. Following are the distribution of principal stresses within the fracture element.

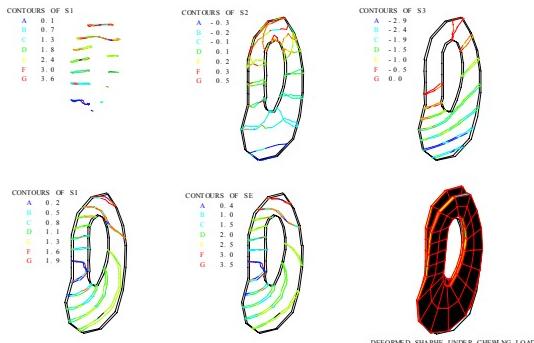


Fig.9 Principal stress contours and the deformed shape of the section passing through the fracture.

The deformation at the fracture was seen to be effected by a number of factors one of which is the elastic modulus of the plate. A parametric study has also been conducted as the following.

IV. RESULTS OF THE PARAMETRIC STUDY

The results of the parametric study are given through the Fig'10-14. In Fig.10 it is seen that when a relatively soft material such as gold was selected for the plate, stresses developed around the 2nd and 3rd screws were seen be increased, while 1st and 4th screws were sharing comparatively lower stresses.

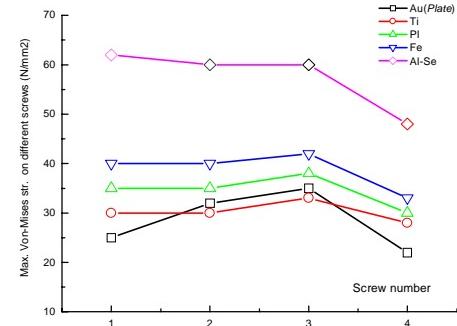


Fig.10 Distribution of maximum von -Mises stresses at screws for different miniplate material properties

However, when a titanium plate was used, it was observed that the 3rd screw had the highest stress among the other three. Generally 4th screw had lowest stress and 3rd one had the highest values in all cases.

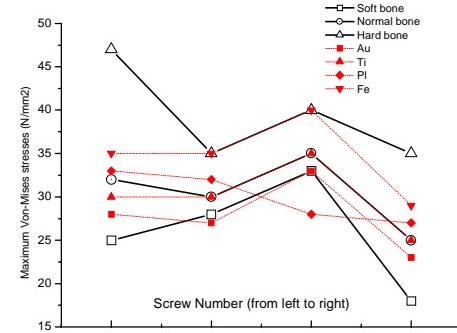


Fig.11 The von Mises stresses developed at screws for different material properties

Two different data sets are shown in the Fig.11. The solid lines correspond to the results of a special case, the particular use of the titanium as a fixation material. The dashed lines indicate the effects of different material properties on the stresses developed at screws

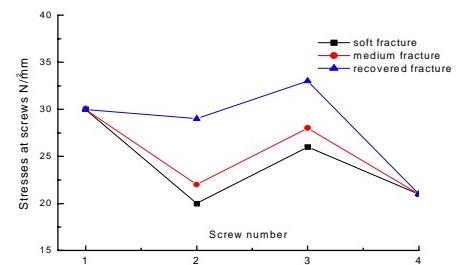


Fig.12 The stresses developed at screws for different healing phases (Use of Titanium for fixation)

The effects of different healing phases were also studies and plotted in the Fig.12. Results indicate that the stresses developed at 1st and the 4th screws do not change during the healing period. However the initial stresses (just after the surgical operation) at 2nd and 3rd screws decrease as the fracture is recovered.

Infact for all cases, a total of four screw were used.

The effects of using less screws and their configurations were also studied and the results are demonstrated in the Fig.13.

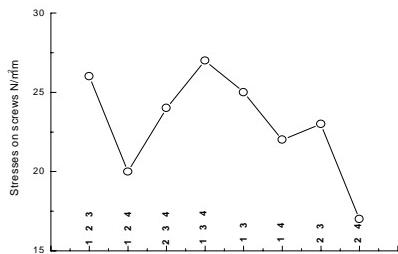


Fig.13 Maximum stresses developed at screws for different screw combinations.

As seen from the figure, the best solution is the 1,2,4 combination.

V. RELATED RESEARCHES : A Review

In the field of oral and maxilo-facial surgery, lag screw and miniplate are commonly used by the surgeon for the fixation of mandibular fractures.

The lag screw technique was numerically studied by [5] for the design and selection of the screws so as to transfer the tensile force to the thin cortical bone. Similarly [6] developed a 3D FEM of the mandible to simulate and study the bio-mechanical loads of osteosynthesis screws in bilateral sagittal osteotomy. An experimental was conducted by [7] to calibrate the generated 3D FEM and investigate the deformation of the bone under biomechanical loads. Generally it was concluded that 3D FEM's might be satisfactory to represent the biomechanics of bone and screws.

Miniplate osteosynthesis techniques were also used by numerous researchers. Practical applications with titanium plates resulted that 70 % of the fractures out of 17 patients treated with titanium mesh occurred without complication [8]. It was also mentioned that the geometry and the physical and bio-mechanical properties of titanium mesh helped to achieve better stabilization in mandibular fractures. However, even though several mini-plates and screws with different geometric designs and material characteristics are available, the elastic properties of the plate, the number and locations of screws, have not been yet definitely demonstrated.

VI. SUMMARY AND DISCUSSION

In this research , a parametric study has been utilized to determine the effects of different parameters on the healing of the patient. By the use of 2D model it was seen that, for a particular value of loading, the results were dependent on some several parameters such as: Effective length of the plate and the ratio of the modulus of elasticity of the plate to the bone. The model was then extended into 3D to consider some additional factors such as: the hollow character of the bone, geometric and material properties of the fracture, cancellous bone. miniplate and the screw, and also the numbering combinations of the screws. The 2D and 3D models showed agreements up to a certain extend but not fully.

In the future, it is planned to automatically generate a full 3D model of the mandible [9] by referring to the age, the fracture type and also the CT scan finding, to yield patient specific solutions.

VII. CONCLUSION

The investigations on mandibular biomechanics indicated that it was only the cortical bone which reflected the biomechanical properties of the mandible. The effect of cancellous bone was seen to be negligible compared to the cortical bone. The stabilization was improved as the elastic modulus of the plate and screws were increased. However when rigid materials were utilized, excessive stress was observed around the screws causing stress shielding effects. In 4-hole plates when only screw no 1,2,4 and 1,4 were used the stabilization was not jeopardized. In all analysis overloaded screws with potential resorption risks were determined.

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